A Portrait of Oil and Gas Wellbore Leakage in Northeastern British Columbia, Canada

Joshua Wisen[a], Romain Chesnaux[a,1], John Werring[b], Gilles Wendling[c], Paul Baudron[d], Florent Barbecot[e]

[a]Département des sciences appliquées, Université du Québec à Chicoutimi, Québec, Canada, G7H3P7; [b]David Suzuki Foundation, Vancouver, British Columbia, Canada, V6K4S2 ; [c]GW Solutions, Nanaimo, British Columbia, Canada, V9T0H2 ; [d]Département des génie civil, géologique et mines, École Polytechnique de Montréal, Montréal, Québec, Canada, H3T1J4; [e]Département des sciences de la terre, Université du Québec à Montréal, Montréal Québec, Canada, H2L2C4

Submitted to Proceedings of the National Academy of Sciences of the United States of America

Oil and gas well leakage is of public concern primarily due to the perceived risks of aquifer contamination and greenhouse gas (GHG) emissions. This study examined well leakage data from the British Columbia Oil and Gas Commission (BC OGC) to identify leakage pathways and initially quantify incident rates of leakage and GHG emissions from leaking wells. Three (3) types of leakage are distinguished: "surface casing vent flow" (SCVF), "outside the surface casing leakage" (OSCL) and "cap leakage" (CL). In BC, the majority of reported incidents involve SCVF of gases, which do not pose a risk of aquifer contamination but do contribute to GHG emissions. Reported liquid leakage of brines and hydrocarbons is rarer. OSCL and CL of gas are more serious problems, due to the risk of long-term leakage from abandoned wells; some were reported to be leaking gas several decades after they were permanently abandoned. According to the requirements of provincial regulation, 21,525 have been tested for leakage. In total, 2,329 wells in BC have had reported leakage during the lifetime of the well. This represents 10,8% of all wells in the assumed test population. However it seems likely that wells drilled and/or abandoned before 2010 have un-reported leakage. In BC, the total GHG emission from gas SCVF is estimated to reach about 75,000 metric tonnes per year based on the existing inventory calculation; however, this number is likely higher due to underreporting.

a | b | c | d | e

Introduction

All modern oil and gas wells are constructed in a drilled hole ("wellbore"), which may be vertical, deviated, or horizontal. The wellbore typically traverses numerous geologic layers variously containing brines and hydrocarbons. Pipe(s) ("casing") and surrounding sealants (typically Portland cement) are placed in the wellbore to maintain its stability, to protect against collapse and squeezing, and to prevent the movement of fluids between geologic layers. The resulting structure, including the wellbore, constitutes an oil and gas well. The inside of the well is hydraulically connected to the geologic layer targeted for fluid production or injection via holes through the casing. Well design thus allows fluids to be produced (hydrocarbons) or injected (waste disposal or fracking for instance) into the well at depth, while preventing contamination of potable water sources close to the surface (1-2).

In this study, the term "contaminants" refers to any substance located underground that may contaminate surface water, land or air. This includes natural contaminants such as gas, oil, and brines as well as man-made contaminants (injected fluids). An inadvertent hydraulic connection between geologically isolated zones may be established along the well due to deficiencies in its design or construction and loss of integrity over time (2-7). This phenomenon is referred to as wellbore leakage. Wellbore leakage can occur along actively producing wells or wells that have been permanently abandoned after their productive life is over. There are three main consequences of wellbore leakage on the environment and public safety (1): 1- contamination of aquifers and surface waters from gases, brines, liquid hydrocarbons and hydraulic fracturing fluids; 2- contribution to greenhouse gas (GHG) emissions especially from venting methane; and 3- explosion of methane accumulated in poorly ventilated areas. Additionally, venting gases sometimes contain hydrogen sulphide (H_2S) gas, which is poisonous and deadly at high concentrations (8). Wellbore leakage incidents can be either chronic, occurring slowly over long periods, or acute, in which large volumes of fluids are released over a short period of time. An example of the latter case is an uncontrolled flow of fluids from a well that occurs at a rate that results in the immediate commencement of remedial action. Note that for the purpose of this study, leakage will only refer to chronic leakage.

Oil and gas well integrity and wellbore leakage are not new issues to industry (3), but the shale gas sector has recently undergone significant growth made possible through the unconventional technique of horizontal drilling coupled with multistage slickwater hydraulic fracturing. In consequence, increased attention and scrutiny have been brought to the issue of wellbore leakage.

Northeastern British Columbia has been a center of extensive conventional oil and gas production since the 1960's. The region also contains four shale gas basins that are increasingly being exploited (Fig. 1). Since 1995, well operators have been required to test for leakage prior to well abandonment (9). Additionally, since 2010, the Oil and Production Regulation of the province's Oil and Gas Activities Act has required operators to test for leakage after drilling, after recompletion, and during routine maintenance.

To date, no study has attempted to establish wellbore leakage statistics for the entire region of Northeastern BC. The goal of this study is to provide a first-glance portrait of wellbore leakage

Significance

The possibility of leakage from oil and gas wells has raised environmental concerns. There are three major environmental consequences of wellbore leakage: 1- the risk of groundwater contamination from hydrocarbons and brines; 2- the risk of greenhouse gas emissions; and 3- the risk of explosion of leaking methane accumulated in poorly ventilated zones. In this study, oil and gas wellbore leakage data from British Columbia were analyzed in order to quantify the occurrence and pathways of leakage as well as the contribution of wellbore leakage to greenhouse gas emissions.

Reserved for Publication Footnotes

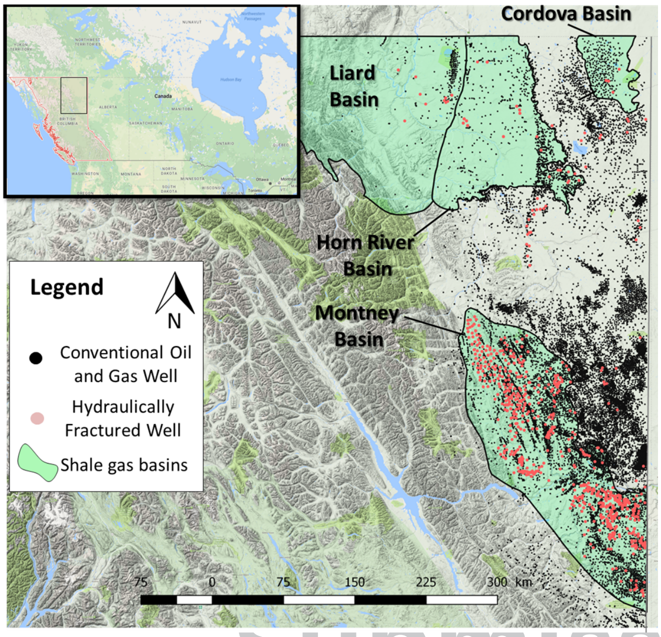

Fig. 1. Distribution of oil and gas wells and shale gas basins in northeastern British Columbia

statistics in BC with the following objectives: 1- determine the percentage of leaky wells in BC classified by fluid type and environmental risk; 2- characterise and quantify well integrity issues and leakage pathways; 3- investigate the influence of well age on the frequency of reported leakage; and 4- quantify the contribution of wellbore leakage to greenhouse gas emissions.

Materials and Methods

Classification of Wellbore Leakage Types. The classification of wellbore leakage types is based on the requirements of oil and gas well construction in British Columbia. These requirements are dictated by the province's *Oil and Gas Activities Act* and enforced by the provincial regulator of the oil and gas industry, the *British Columbia Oil and Gas Commission* (BC OGC). Although this study focuses on BC, it should be noted that drilling and completion operations are relatively similar for all modern oil and gas wells (1-2).

The aim of oil and gas well design is to maintain wellbore stability and to prevent hydraulic communication between geologically isolated zones that are intercepted by the wellbore. This helps to protect shallow aquifers that could be contaminated by deep subsurface fluids. The standard design consists of an outer surface casing that is set and cemented in place below the depth of usable groundwater. Inside the surface casing lies the production casing which conveys production or injection fluids between the target formation and the wellhead (Fig. 2). The production casing may be fully or partially cemented in place and is equipped with an additional replaceable inner production tubing. The wellhead includes a surface casing vent that allows any fluids entering the annular space between the surface and inner casings to vent at the surface rather than build up in or along the well. This type of leakage is referred to as a *surface casing vent flow* (SCVF) and is one of the possible exit points along a well for leakage of either gas or liquid (Fig. 2). Gases exiting the vent will enter into the atmosphere rather than entering into and possibly contaminating surrounding soils or groundwater. These gases are primarily composed of methane and contribute to atmospheric greenhouse gas emissions (1-2, 10). Vented liquids such as brines and liquid hydrocarbons can spread at the surface and infiltrate the soil and the groundwater table below. When gases or fluids leak outside of the outermost surface casing, the contaminants may come into contact with aquifers. In the oil and gas industry, gas leaking around a well is commonly referred to as *gas migration*; however, the industry has no designated term for leakage of liquids around the casing. In this study, we designate all leakage occurring outside of the outermost surface casing, whether it be gaseous or liquid, as *outside of the surface casing leakage* (OSCL). OSCL represents one of the possible exit points for wellbore leakage. Like SCVF of gas, OSCL of gas is considered a possible source of GHG emissions (11).

Wells are abandoned after their operating life comes to an end. The standard method of well decommissioning involves plugging the well, removing the wellhead and then cutting, capping and burying the casing at least 1 meter below the surface (Fig. 3). All perforated intervals of the well and all exposed porous geological zones of the well must be covered or isolated. This includes covering open-hole sections of porous zones, and setting a cement retainer within 15 m above perforated zones. Additionally, sections of wells with uncemented liner must be cement-squeezed in order to isolate porous zones. It should be noted that in the past, abandonment procedures may have been less stringent. A more detailed explanation of abandonment procedures can be found in the Directive 20 of the Alberta Energy Regulator, which also serves as the procedure for well abandonment in British Columbia.

The wellhead assembly is replaced by a vented cap covering the production and surface casings. Any leakage that would manifest itself as SCVF on an active well will, in a decommissioned well, leak instead from the vented cap into the overlying soil, rather than venting directly into the atmosphere. Similarly, fluids can leak out of the inner production casing though the vented cap and into the soil. In this study, we identify leakage through the vented cap of abandoned wells as a possible exit pathway for leakage. This exit pathway is referred to as *cap leakage* (CL). Depending on the depth of the buried vented cap relative to the groundwater table, CL could represent a source of groundwater contamination. Similar to active wells, abandoned wells can also emit OSCL. In general, we consider any leakage from an abandoned well as a possible source of groundwater contamination. Additionally, we consider any gas leaking from an abandoned well as a possible source of GHG emissions.

Wells that are no longer in operation, but which have not yet been abandoned, are considered suspended (or shut-in). Suspended wells are similar to active wells in that their wellhead and vent remain in place; in other words, they are still intact. For this reason, suspended and active wells are considered a single well type; in this study, for reasons of brevity, they are referred to simply as active wells.

Occurrences of wellbore leakage in this study are described according to "entry" and "exit" pathways for active and abandoned wells as shown in Figs. 2 and 3, respectively. "Entry" refers to underground contaminants entering into the well. We have identified seven possible entry pathways of contaminants along the well (Figs. 2 and 3):

1) Target formation that the well is drilled to exploit; either along or below the cement of the production casing.

2) Cemented intermediate formations above the target formation.

3) Un-cemented intermediate formations.

4) Cemented shallow formations above the surface casing shoe.

5) Production casing failure. This allows production fluids to enter directly into the outer surface casing.

6) Wellhead seal failure. These are integrity problems occurring at the wellhead, and therefore applicable only to active wells, but not to abandoned wells.

7) Plug failure in abandoned wells.

"Exit" pathways refer to the flow of fluids from the well outwards to the environment, either into the atmosphere, shallow aquifers, surface waters or soil. There are three exit pathways for contaminants: surface casing vent flow (SCVF), outside of the surface casing leakage (OSCL), and cap leakage (CL). In all three cases, leakage can be either liquid leakage (brines and/or hydrocarbons) or gas leakage (principally methane).

Data Sources. All data analyzed in this study were extracted from databases maintained by the BC Oil and Gas Commission (BC OGC). BC OGC is the provincial regulator of the oil and gas industry; its data are publicly available upon request. The BC OGC designates each well in the province by a unique Well Authorization Number (WAN) which can be used to search for data on that specific well among the three databases accessed for this study: Wellbore Leakage Database (*SI Appendix 1, 2 and 3*), Integrated Resource Information System (IRIS) and E-library.

Since 1995, oil and gas operators in BC have been required to submit to the BC OGC the results of all well tests that are positive for leakage. The BC OGC collects and summarizes the results of leakage testing in the *wellbore leakage database* (which includes SCVF, OSCL and CL). An extract of the wellbore leakage database is shown in Table 1. It contains a column labeled "Flow Type" to identify the type of fluid found to be leaking from the well: gas, hydrocarbon (hydrocarbon refers to liquid hydrocarbons), brines or freshwater. The flow rate column corresponds uniquely to SCVF. The spreadsheet also contains a separate column for the reporting of *gas migration;* in the industry, gas migration represents any leakage of gas that is detected in the soil around the well, rather than issuing from the surface casing vent (SCVF). In the case of active wells, gas migration necessarily equates to OSCL; however, for abandoned wells, gas migration could be either OSCL or CL. Regarding liquid leakage, the database does not include a separate column corresponding to OSCL. In order to verify the exit points for all cases of liquid leakage or for abandoned wells with gas leakage, it was necessary to delve further into the database documents, most notably the completion workover reports of these wells available in the E-library database. Entries that had no reported fluid types were considered negative test results, and therefore not considered to be leaking.

The completion workover reports analysed in the E-library describe the remedial actions that were taken while re-entering the well in order to repair the leakage. Analysis of the completion workover reports allowed us to determine the entry and exit points of leakage based on observations and the remedial steps that were taken to address the issue. One workover method for repairing leaking wells is to squeeze cement; this consists in

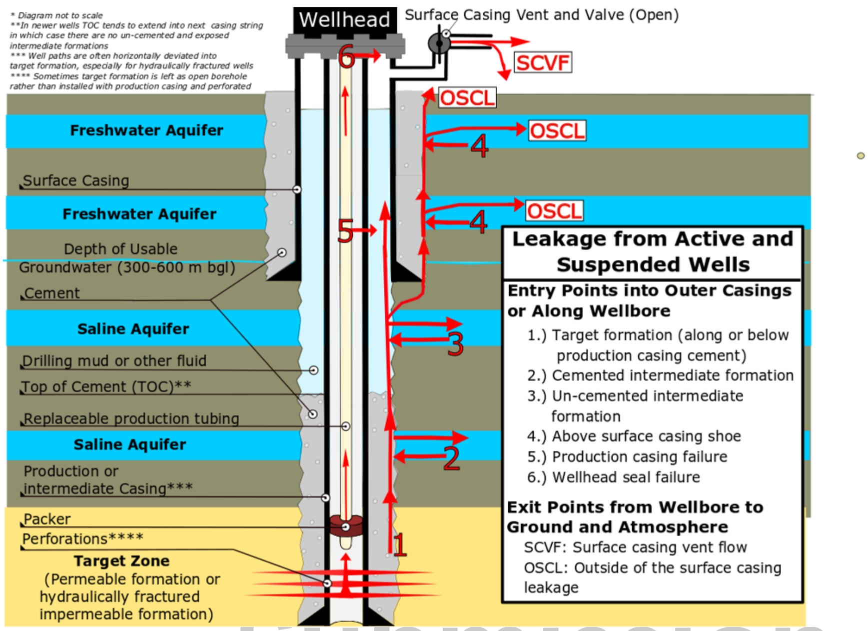

Fig. 2. Schematic of an active well with leakage pathways classified according to entry and exit points along the wellbore. Figure not to scale

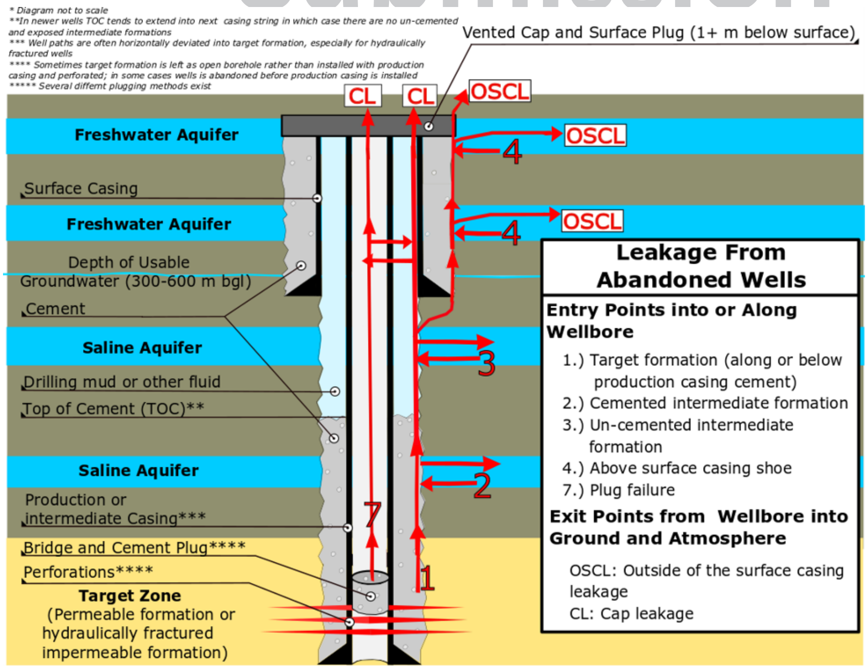

Fig. 3. Schematic of an abandoned well and leakage pathways classified according to entry and exit points along the wellbore. Figure not to scale

Table 1. Sample data extracted from the wellbore leakage database.

Well Authorization Number (WAN)	Analysis Date	Flow Type	SCVF Flow Rate (m^3/day)	Gas Migration
168	March 1 2012	Gas	9.5	
1220	February 7 2012	Salt Water		
2183	June 12 2016			No
2249	September 23 2013	Gas	0	
2249	October 26 2016	Salt Water		No
2283	July 7 2016			Yes
2287	March 30 2014	Gas	0.2	Yes
6136	November 13 2000	Hydrocarbon	22	Yes

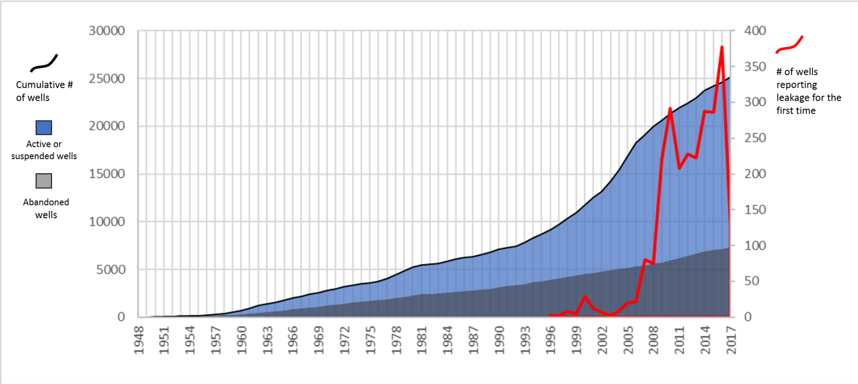

Fig. 4. Cumulative number of wells and number of reported leaky wells per year. The sharp increase in 2010 of the number of wells reporting leakage corresponds to stricter testing and reporting requirements

Table 2. Number and percentage of reported incidents by fluid types and exit pathways for active oil and gas wells in British Columbia

	SCVF only	SCVF and OSCL	OSCL only	Total
Gas	90.7% (2,105)	5.4% (126)	0.5% (12)	96.6% (2,243)
Gas and Liquid	1.3% (30)	0.1% (3)	0.04% (1)	1.5% (34)
Liquid	1.9% (43)	0.04% (1)	0.04% (1)	1.9% (45)
Total	93.8% (2,178)	5.6% (130)	0.6% (14)	100.0% (2,322)

SCVF: surface casing vent flow; OSCL: outside the surface casing leakage

Table 3. Number and percentage of reported incidents by fluid types and exit pathways for abandoned oil and gas wells in British Columbia.

	CL only	CL and OSCL	OSCL only	Total
Gas	57.1% (4)	42.9% (3)	0.0% (0)	100.0% (7)
Gas and Liquid	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
Liquid	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
Total	57.1% (4)	42.9% (3)	0.0% (0)	100.0% (7)

CL: casing leakage; OSCL: outside the surface casing leakage

Table 4. Details of the 7 abandoned wells reporting leakage in BC

Well Authority Number	Reported Initial Abandonment Date	Any leakage issues reported prior to abandonment?	Date of first reported leakage
2283	1968-03-07	No	2015-04-29
7858	1992-06-26	No	2009-07-10
8818	1996-01-14	No	2015-09-09
12307	2002-11-23	No	2016-12-08
2287	2005-02-24	No	2013-06-19
19071	2006-01-19	No	2013-10-10
5100	?	No	2010-07-01

perforating the leaky interval and injecting it with cement. These leaky intervals could have deficient cementing or be lacking cement altogether. We investigated the completion workover reports from a representative sample of leakage pathways for all active wells.

Lastly, an array of data on well location, construction, completion, production and abandonment can be found in the BC OGC's Integrated Resource Information System (IRIS). This study investigates all available data in the IRIS until the end of 2017.

The raw data from the wellbore leakage database is presented in *SI Appendix 1* of supporting information whereas the *SI Appendix* 2 of supporting information presents the results and integration of all the available datasets listed by WAN.

Results and Discussion

Wellbore Leakage Incident Rates. By the end of 2017, in British Columbia 25,119 wells had been drilled, 3,594 were drilled and badnoned before 1995 (Fig. 4). There are 2,322 cases of reported leakage from active wells and 7 reported instances from abandoned wells (*SI Appendix 1 and 2*). As previously stated, reporting of wellbore leakage in BC only goes as far back as 1995 (Fig. 4). This corresponds to the beginning of the datbase as well as the year that operators in BC were first required to test for surface casing vent flow leakage prior to abandonment. An increase in reported instances occurs in the late 2000s, potentially due to increased drilling activity and self-reporting from industry. This increase in reported leakage continued after 2010, the year of new regulations requiring leakage testing after drilling and during routine maintenance. 2010 is also the year that operators were first required to report OSCL of gas. However, testing for OSCL of gas in BC is only required when there are visible signs such as dead vegetation or bubbling in water around the wellhead (12). For abandoned wells there is currently no requirement for leakage testing.

Leakage testing is generally self-reported by industry and reporting is only required for positive test results. If we consider all wells in BC except those abandoned before 1995, the year when leakage reporting began in the province, this represents a total test population of 21,525 wells. The 2,322 reported cases of active wells with leakage therefore represent a leakage incident rate of 10.8%. This figure is more than 2 times higher than the leakage occurrence rate of 4.6% determined by other researchers for wells in the neighbouring province of Alberta (4). These researchers also point out that their number could be influenced by less stringent testing and reporting requirements in the past. According to these authors, it is plausible that many wells in Alberta abandoned before 1995 could present unreported or undiscovered leakage (4) similar to what is observed in BC. In Alberta as in BC, leakage is self-reported by industry (4). For Alberta, however, it is unclear if the self-reporting by industry necessarily includes the submission of negative test results, or if it is limited only to the submission of data for wells testing positive for leakage, as is the case in BC. This is an important point, given

Table 5. Percentages and numbers of occurrences of leakage in different types of pathways for active wells, as described in Fig. 2. Percentages based on available reports from a sample of 29 studied wells.

		Exit Points			
		SCVF only	SCVF and OSCL	OSCL only	Total
Entry Points	1: Target Formation	0.0 % (0)	0.0 % (0)	0.0 % (0)	0.0 % (0)
	2: Cemented Intermediate Formation	3.4 % (1)	0.0 % (0)	0.0 % (0)	3.4 % (1)
	3: Un-cemented Intermediate Formation	34.5 % (10)	0.0 % (0)	0.0 % (0)	34.5 % (10)
	4: Above surface casing shoe	0.0 % (0)	0.0 % (0)	6.9 % (2)	6.9 % (2)
	5: Production casing failure	41.4 % (12)	3.4 % (1)	0.0 % (0)	44.8 % (13)
	6: Wellhead seal failure	10.3 % (3)	0.0 % (0)	0.0 % (0)	10.3 % (3)

Table 6. Percentages and numbers of occurrence of leakage in different types of abandoned wells, as described in Fig. 3. Percentages based on available reports from 7 studied wells.

		Exit Points			
		CL only	CL and OSCL	OSCL only	Total
	1: Target Formation	0.0 % (0)	0.0 % (0)	0.0 % (0)	0 % (0)
	2: Cemented Intermediate Formation	14.3 % (1)	14.3 % (1)	0.0 % (0)	28.6 % (2)
Entry Points	3: Un-cemented Intermediate Formation	42.9 % (3)	14.3 % (1)	0.0 % (0)	57.2 % (4)
	4: Above surface casing shoe	0.0 % (0)	0.0 % (0)	0.0 % (0)	0 % (0)
	7: Plug Failure	0.0 % (0)	14.3 % (1)	0.0 % (0)	14.3 % (1)

that a comparison study between the leakage database in BC and the results of a field campaign have shown that approximately half of wells with detected leakage do not appear in the database (10, 13). This suggests that the true percentage of leaky wellbores in BC could be much higher than the 10.8% calculated from the theoretical test population. We will see in a subsequent section of this article that the rate of reported leakage could also be a function of the timing and frequency of testing, which are linked to drilling and abandonment dates.

Tables 2 and 3 summarize the wellbore leakage statistics for all active and abandoned wells in BC, according to leakage fluid types and exit pathways, respectively. The majority of these leakage incidents (90.7%) involves SCVF of gas, which does not pose a risk of aquifer contamination, but which does contribute to GHG emissions. OSCL (outside the surface casing leakage) of gas is rarer and is usually accompanied by SCVF (surface casing vent flow) of gas. 5.4% of cases involve a combination of SCVF and OSCL of gas, whereas approximately 0.5% involve only reported OSCL of gas.

Liquid leakage in active wells is rarer and is commonly accompanied by gas leakage. In total, 3.42% of leakage instances involve liquid leakage or a combination of gas and liquid, mostly in the form of SCVF (3.2%). Only 6 instances involving OCSL of liquid were discovered (including a combination of OSCL and SCVF as well as liquid and gas), representing 0.22% of active well leakage. The lesser number of instances of liquid leakage that are reported could be explained by the fact that liquid leakage is less likely to reach the surface where it can be detected. Indeed, liquid leakage requires a certain degree of hydraulic head in order to reach the surface; furthermore, liquid leaking along a wellbore will have a tendency to flow into a transmissive interval along the wellbore.

Reported leakage of abandoned wells is rarer than for active wells. At the end of 2017 there were 7,268 abandoned wells in BC. Of these, only 7, or 0.1%, reported leakage after their abandonment date, in the form of CL or OSCL of gas (Tables 3 and 4). No liquid leakage from abandoned wells was reported. It is difficult to determine if this low rate of leakage occurrence for abandoned wells is due to the fact that they actually leak less, or that leakage from abandoned wells is simply less frequently discovered and reported. Although current regulations stipulate that all incidences of leakage must be repaired prior to well abandonment, there is no program in place in Canada for monitoring wellbore leakage in wells once permanently buried and abandoned (1). It is unclear why and how the 7 abandoned wells under investigation in this study were identified to be leaking. Furthermore, it is important to note that the majority (4 wells) of these 7 wells were abandoned after 1995, when leakage testing prior to abandonment became mandatory (Table 4). Therefore, either the leakage in these 4 wells was not properly identified and repaired prior to abandonment, or leakage developed along the well later after abandonment.

Several field investigations conducted in other study zones outside of BC indicate much higher incident rates of abandoned well leakage than those estimated in this study (6-7, 14-15). In general, field investigations tend to find that plugged abandoned wells, such as those in BC, leak far less than unplugged abandoned wells (7, 14). Still, the percentage of abandoned and plugged wells with detectable positive methane flow rates ranges from 0.8% (14) to 69% (7) which correspond, respectively, to 8 and 700 times the incident rate of 0.1% calculated in this study. The incident rate of leakage from abandoned wells could be even higher when considering that field investigations measuring methane fluxes at the surface may be unable to detect leakage, due to oxidation and dispersion of methane in the subsurface (15, 16). In general, it is difficult to quantitatively compare the results of our inventory study with direct field measurements, as the database does not provide any information on testing methodology and detection limits. However, it is likely that the true percentage of abandoned and leaking wells in BC is higher than our inventory estimates, considering the results of these field investigations and considering the absence of a monitoring program in BC.

Wellbore Leakage Pathways. Two sub-analyses were conducted based on a sample of 29 active well leakage incidents and 7 abandoned well leakage incidents extracted from the databases; the 29 incidents occurring in active wells were chosen based on availability of completion workover reports containing sufficient detail. The goal was to obtain a preliminary idea of the proportion distribution of the various pathways for well leakage, i.e., how frequently one leakage pathway occurs versus another. The percentage distributions of leakage incidents by type of pathway are

Table 7.

	Abandonment Date						
Drill Date	Percentage (%) of intact wells tested upon abandonment and found to be leaking (number leaking/total)			Percentage (%) of intact wells tested after drilling during routine maintenance and upon abandonment and found to be leaking (number leaking/total)			Total
	1995–1999	2000–2004	2005–2009	2010 - 2014	2015 - 2017	Not Abandoned	
1945 - 1949	0.0 (0/1)						0.0% (0/1)
1950 - 1954	0.0% (0/1)	0.0% (0/4)	0.0% (0/3)	0.0% (0/2)		0.0% (0/17)	0.0% (0/27)
1955 - 1959	0.0% (0/11)	0.0% (0/3)	0.0% (0/13)	5.9% (1/17)	0.0% (0/4)	12.5% (18/144)	9.9% (19/192)
1960 - 1964	0.0% (0/20)	3.6% (1/28)	4.5% (1/22)	12.5% (5/40)	0.0% (0/4)	5.4% (26/480)	5.6% (33/594)
1965 - 1969	0.0% (0/25)	0.0% (0/13)	4.9% (2/41)	10.0% (6/60)	13.0% (3/23)	10.9% (35/322)	9.5% (46/484)
1970 - 1974	0.0% (0/26)	0.0% (0/28)	6.9% (2/29)	6.1% (2/33)	28.6% (6/21)	13.3% (35/264)	11.2% (45/401)
1975 - 1979	0.0% (0/29)	0.0% (0/33)	7.3% (4/55)	15.4% (14/91)	5.9% (1/17)	14.0% (74/529)	12.3% (93/754)
1980 - 1984	0.0% (0/34)	0.0% (0/21)	3.0% (1/33)	12.5% (6/48)	7.7% (1/13)	10.6% (40/378)	9.1% (48/527)
1985 - 1989	0.0% (0/22)	0.0% (0/19)	0.0% (0/25)	13.6% (6/44)	4.0% (1/25)	7.2% (34/469)	6.8% (41/604)
1990 - 1994	0.0% (0/47)	0.0% (0/39)	3.1% (1/32)	7.5% (7/93)	15.6% (5/32)	9.1% (77/848)	8.2% (90/1,091)
1995 - 1999	0.2% (1/505)	0.0% (0/96)	3.8% (3/79)	5.3% (11/208)	14.0% (6/43)	8.2% (139/1,697)	6.1% (160/2,628)
2000 - 2004		0.2% (1/411)	3.7% (5/135)	3.9% (12/307)	9.4% (13/139)	8.5% (300/3,526)	7.3% (331/4,518)
2005 - 2009			0.0% (0/197)	5.6% (11/195)	11.5% (16/139)	13.8% (637/4,600)	12.9% (664/5,131)
2010 - 2014				6.9% (2/29)	18.8% (3/16)	20.5% (633/3,083)	20.4% (638/3,128)
2015 - 2017					0.0% (0/9)	7.9% (114/1,436)	7.9% (114/1,445)
Total	0.1% (1/721)	0.3% (2/695)	2.9% (19/664)	7.1% (83/1,167)	11.3% (55/485)	12.2% (2,162/17,793)	10.8% (2322/21,525)

Percentage of intact wells reporting leakage in British Columbia sorted by drill date and abandonment date.

shown in Table 5 for 29 active wells and in Table 6 for 7 abandoned wells, respectively.

Leakage Pathways in Active Wells. The completion workover reports of 29 active wells with leakage from the E-library were investigated. The most commonly reported entry pathway occurs through deficiencies in the production casing caused by corrosion or rupture of casing strings (44.8%). This typically resulted in SCVF (surface casing vent flow); however, in one incident, leakage from deficiencies in the production casing exited in the form of OSCL (outside the surface casing leakage). Chemical, electrochemical and mechanical corrosion of steel casings in contact with highly saline and often acidic subsurface liquids is a common phenomenon (1). This corrosion can also occur in cemented sections of the wellbore, typically along, but not restricted to, zones of poor cement quality (Watson and Bachu 2009). These types of leaks were often detected by pressure testing of the production casing.

Leakage from un-cemented intervals along the production casing occurred in 34.5% of the cases. Lack of cementing allows for intermediate subsurface fluids to enter unimpeded into the annular space. These always resulted in SCVF as an exit point. In these cases, leakage was repaired by squeeze-cementing the unprotected intervals of the casing. Leakage due to the failure of wellhead seals accounted for 10.3% of reported incidents. In these cases, the leakage was remediated by replacing or repairing the wellhead.

Two cases of leakage originating above the surface casing shoe were reported (6.9% of reported incidents). In one of these two incidences, leakage was detected during drilling and completion operations before the production casing was installed (Well 2552). In the other incident, the surface casing was not completely cemented to the surface as required, which allowed freshwater from an aquifer located at a depth of 30 to 40 meters to enter directly into the well's outer annulus (Well 22912).

Lastly, the type of pathway least frequently reported for leakage was through a production casing failure where the annulus was cemented. Only a single completion workover report among the 29 was found where SCVF was repaired by squeeze-cementing an already cemented interval. Prior to remediation, this leakage exited the well in the form of SCVF.

Leakage Pathways in Abandoned Wells. Table 6 summarizes the observed leakage pathways for abandoned wells. As previously mentioned, all cases of abandoned well leakage involved gases rather than liquids. The majority of cases of abandoned well leakage originates from uncemented intervals below the surface casing (57.2%). The next most common entry points were cemented intervals below the surface casing (28.6%) and plug failure (14.3%), respectively. There were no reported cases

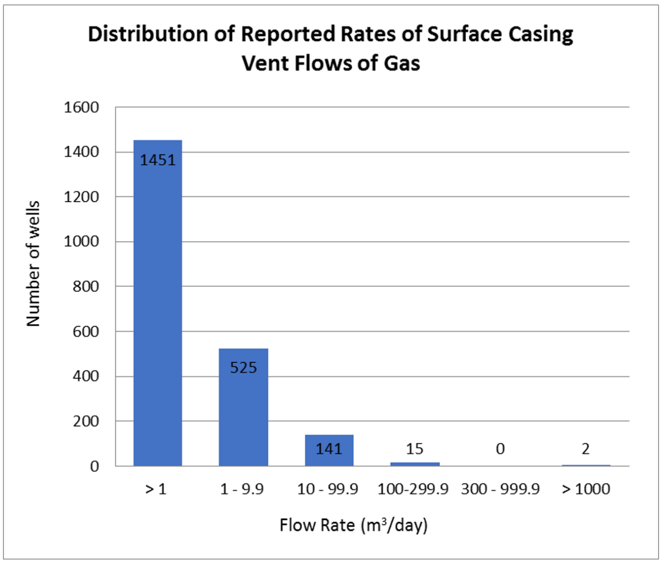

Fig. 5. Histogram of incidents of reported SCVF of gas in the wellbore leakage database

of abandoned well leakage originating above the surface casing shoe. In all cases, leakage exited the well in the form of CL. In about half of these cases, leakage also exited the well in the form of OSCL in addition to CL.

Influence of Well Age on Leakage Occurrence

Table 7 shows the reported percentage and number of active well leakage occurrences as a function of age based on a matrix of drill and abandonment dates. An increase in well age can be noted by reading the table either vertically down or horizontally to the right along the matrix, where well age is calculated by subtracting the abandonment date by the drill date. Table 7 does not investigate the timing of first reported leakage, except for wells that were drilled and abandoned in the same date range, in which case we know that leakage occurred within the first 5 years of the well's existence. This table also shows the distribution of leakage occurrence by well age, interpolated by drill date relative to the end of 2017, for non-abandoned wells. Non-abandoned wells are those wells that were active or suspended at the end of 2017 and which make up the majority of wells in the province (17,793 wells).

According to regulation, all wells in this table should have been tested for leakage at least once either after drilling, during routine maintenance, during recompletion or upon abandonment. The requirement for testing after drilling and routine maintenance has been in effect since the beginning of 2010. As previously discussed, the leakage occurrence rate of the theoretical test population is therefore 10.8%; this percentage is calculated based on 2,322 wells with reported leakage out of the 21,525 that were either abandoned after 1995 (3,732 wells) or are still active (17,793 wells). Note that this total of 2,322 does not include the 7 wells that were found to be leaking after abandonment because Table 7 only deals with leakage detected on active wells.

If we consider only wells drilled after 2010, there is a relationship between well age and the reported incident rate of leakage, reading in both the vertical and horizontal directions of the table. However, the relationship between well age and leakage occurrence is less clear in the remainder of the matrix (wells drilled before 2010). Instead, the occurrence of leakage seems more strongly correlated with regulatory changes implemented in 2010.

According to regulation, wells abandoned before 2010 were at least tested upon abandonment; however, not necessarily during the lifetime of the well. Wells that were active or abandoned after 2010 have theoretically been tested during routine maintenance of the well, recompletion of the well, and upon abandonment where applicable. Wells drilled after 2010 were additionally tested after drilling. Table 7 reveals that there is a correlation between the leakage incident rates and the required frequency of testing according to regulation.

The group of wells that report the least amount of leakage are those abandoned prior to 2010 when routine testing and maintenance became mandatory. In general, Table 7 indicates that regardless of drill date, wells abandoned before 2010 report less leakage than wells abandoned after 2010. This increase in reported leakage does not appear to be linked to well age because the increase is only observed in a horizontal direction of the table.

Looking at wells that were abandoned after 2010 or never abandoned, there is no clear relationship between well age and leakage occurrence in either a horizontal or vertical sense, with the exception of wells drilled after 2010.

The group of wells that report the highest percentage of leakage are those drilled after 2010, which are the newest wells in the province.

We feel that it should be questioned whether older wells have less leakage during their lifetime than newer and younger wells. The data appear to be strongly influenced by the different regulations making their appearance at different dates, casting doubt on the adequacy of well-testing practices and the accuracy of well-testing data for wells drilled before 2010.

Under-reporting of wellbore leakage in BC is an issue that was raised in a previous study (13) which showed that approximately half of wells that tested positive for SCVF gas leakage did not appear in BC's OGC database; almost all of these wells that were missing from the leakage database were drilled before 2010.

Table 7 also suggests that wellbore leakage from wells abandoned before 2010 is under-reported. This is supported by the observation that some wells have reported leakage after being abandoned, despite theoretically having been tested for leakage prior to their abandonment. All of the abandoned wells reporting leakage in Table 7 were abandoned prior to 2010. For all these reasons, the true percentage of leaky wells is unknown but is likely higher than the 10.8% estimated in the total of this table. The figure of 10.8% should be considered a base minimum.

Greenhouse Gas Emissions

As mentioned, surface casing vent flow of gas is the most commonly reported type of leakage in the BC OGC database. Individual wells in the database often have multiple entries in the table listing gas leakage, referring to multiple testing events. In our calculations for this study, we used only the most recently reported value (and not an average of all the reported rates for each well). Additionally, we have removed from our calculations all wells that have been remediated. We consider a well to be successfully remediated if the date of last remedial action post dates the last reported leakage.

The mean reported surface casing vent flow rate is 5.9 m^3/day; however, most vent flows are less than 1 m^3/day (Fig. 5). To provide some perspective, an average cow produces at least 0.25 m^3/day of methane (17). Therefore, the mean average leaky well in BC is equivalent to 24 head of cattle. A SCVF rate of 5.9 m^3 per day and per well corresponds to a mass rate of 3.87 kg per day and per well or 1.4 metric tonnes per year and per well for British Columbia, assuming that the exiting gas is composed entirely of methane and considering that the density of methane is 0.656 kg/m^3 (at standard conditions). This methane rate equates to 35 metric tonnes of CO_2 equivalent per well and per year based on the Intergovernmental Panel on Climate Change's estimate of the Global Warming Potential (GWP) of methane (18) which estimates that 1 kg of methane is equivalent to the GWP of 25 kg of carbon dioxide.

The BC OGC database records 2,134 wells with un-remediated gas SCVF. Multiplying 2,134 wells by an average vent flow of 35 metric tonnes of CO_2 equivalent per year and per well equates to a total GHG emission of 74,690 metric tonnes of CO_2 equivalent per year emitted by wells with un-remediated gas SCVF. This number can also be calculated by summing the total of all non-remediated surface casing vent flows.

In 2016, BC's provincial GHG inventory reported a total emission of 61,300,000 tonnes of CO_2 equivalent per year for all human activity (22). Therefore, based on inventory calculations, emissions from SCVF account for 0.12% of the province's total GHG emissions. Considering that the per capita GHG emissions for Canada have been established at approximately 15 metric tonnes of CO_2 per year, the GHG emission from wellbore leakage in BC is equivalent to that emitted by a Canadian town of 5,000 people. It should not be forgotten that these figures represent a base minimum, because as mentioned previously, the number of wells with SCVF is likely under-reported. It should also be noted that wellbore leakage is not the only source of GHG emissions from upstream oil and gas activity; intentional release of gas from flaring and pneumatic devices also contributes significantly to total GHG emissions (10, 23).

Conclusions

A total of 2,329 oil and gas wells in northeastern BC have reported leakage. However, the actual number is likely higher due to underreporting.

Most reported leakage occurs in the form of gas surface casing vent flow (SCVF), which does not pose a risk of aquifer contamination but does contribute to greenhouse gas (GHG) emissions. Based on the data provided by the BC OGC, the total volume of GHG emissions from well leakage in BC is estimated to reach approximately 74,690 metric tonnes per year CO_2 equivalent. This would make wellbore leakage a relatively minor contributor to the total GHG emissions in the province, keeping in mind that true emission rates and volumes could be higher due to under-reporting of leakage. Reported liquid leakage of brines and hydrocarbons is rarer. In most cases, the risk would appear to be greatly reduced by fully cementing the production casing to the surface; however, full-length cementing increases the cost of constructing the well and in some cases, the increased cement fluid pressure may decrease the quality of the cementing operation due to the lost circulation of cementing fluids during installation (24).

Outside of the surface casing leakage (OSCL) of gas from abandoned and active wells appears to be a more serious problem. Gas leakage is most readily identifiable when it manifests itself at the surface near the wellhead (2). However, gas leaking into aquifers could remain undetected. A recent 72-day methane gas injection experiment showed that even if a signifcant portion of methane may vent to the atmosphere, an equal portion may remain in groundwater (25). Of particular concern is the risk of long-term development of leakage from wells that are cut and capped below the surface for permanent abandonment. For some wells, there have been reports of leaking gas several decades after they were permanently abandoned. Additionally, wells abandoned before 2010 report less leakage than those abandoned after 2010, which seems to indicate that exisiting leakage was either undetected or unreported prior to abandonment. In Canada there is no requirement to monitor wells for leakage following their abandonment (2), despite the fact that gas leakage from abandoned wells in the province is a well-documented phenomenon (Table 5). It is possible and even probable that the number of abandoned wells leaking gas is much higher than the 7 documented cases mentioned in this study, due to the number of untested abandoned wells. Unlike the field investigations conducted by other researchers (6-7, 14-15), there has been no field investigation carried out in BC directly monitoring leakage from abandoned wells. Further efforts should be dedicated to such monitoring of abandoned wells.

Acknowledgements.
The authors would like to thank the MITACS Accelerate Program, which partnered the David Suzuki Foundation (DSF) and GW Solutions inc. to provide funding for this research project. We would also like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC), and the Fonds de Recherche du Québec - Nature et technologies (FRQNT) which also provided research grant funding. Two anonymous reviewers and an Editor are thanked for their thorough review of the manuscript, which has contributed to improving the quality of the manuscript. Ms. Josee Kaufmann is also thanked for editorial collaboration.

1. Dusseault MB, Jackson RE, Macdonald D (2014) Towards a road map for mitigating the rates and occurrences of long-term wellbore leakage. Waterloo, ON, Canada: University of Waterloo, 69p.
2. Dusseault M, Jackson R (2014) Seepage pathway assessment for natural gas to shallow groundwater during well stimulation, in production, and after abandonment. *Environ Geosci* 21(3): 107-126.
3. Dusseault, MB, Gray MN, Nawrocki PA (2000). *Why oilwells leak: Cement behavior and long-term consequences*. Society of Petroleum Engineers Conference Paper, SPE-64733-MS, 10.2118/64733-MS.
4. Watson T, Bachu S (2009) Evaluation of the potential for gas and CO_2 leakage along wellbores. *Society of Petroleum Engineers, Drilling and Completion* 24(1): 115-126.
5. Davies RJ, et al. (2014) Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. *Mar Pet Geol* 56: 239-254.
6. Kang M, et al. (2014). Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania. *Proc Natl Acad Sci USA* 111(51): 18173-18177.
7. Kang M, et al. (2016). Identification and characterization of high methane-emitting abandoned oil and gas wells. *Proc Natl Acad Sci USA* 113(48): 13636-13641.
8. BC OGC (British Columbia Oil and Gas Commission) (2014). Engineering/Technical Investigation Report: Well Failure at Terra Wilder. Available at: https://www.bcogc.ca/node/129-37/download.
9. Oil and Gas Activities Act. Victoria, British Columbia: Queen's Printer. Available at: http://www.bclaws.ca/civix/document/id/complete/statreg/08036_01.
10. Werring J (2018) *Fugitives in Our Mist: Investigating fugitive emissions from abandoned, suspended and active oil and gas wells in the Montney Basin in northeastern British Columbia.* Vancouver, Canada: David Suzuki Foundation.
11. Erno B, Schmitz R (1996) Measurements of soil gas migration around oil and gas wells in the Lloydminster area. *J Canadian Petroleum Technol* 35: 37-45.
12. BC OGC (British Columbia Oil and Gas Commission) (2019) *Oil and Gas Activities Operation Manual 2019.* Victoria, BC, 2019. Available at: https://www.bcogc.ca/industry-zone/documentation/oil-and-gas-activity-operations-manual.
13. Wisen J, et al. (2017) A Portrait of Oil and Gas Wellbore Leakage in Northeastern British Columbia, Canada. *70th Canadian Geotechnical Conference and 12th Joint Canadian Geotechnical Society/IAH Canadian National Chapter Groundwater Conference, GeoOttawa,* Ottawa.
14. Townsend-Small A, Ferrara TW, Lyon DR, Fries AE, Lamb B.K (2016) Emissions of coalbed and natural gas methane from abandoned oil and gas wells in the United States. *Geophys Res Lett* 43(5): 2283-2290.
15. Schout G, Griffioen J, Hassanizadeh SM, de Lichtbuer GC, Hartog N (2019) Occurrence and fate of methane leakage from cut and buried abandoned gas wells in the Netherlands. *Sci Total Environ* 659: 773-782.
16. McMahon PB, Thomas JC, Crawford JT, Dornblaser MM, Hunt AG (2018) Methane in groundwater from a leaking gas well, Piceance Basin, Colorado, USA. *Sci Total Environ* 634: 791-801.
17. Johnson KA, Johnson DE (1995) Methane emissions from cattle. *J of Animal Sci* 73(8): 2483-2492.

IPCC (Intergovernmental Panel on Climate Change) (2000) Good *Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme. Available online at: http://www.ipcc-nggip.iges.or.jp/public/gp/english/.

19. US EPA (2018) *Greenhouse Gas Emissions from a Typical Passenger Vehicle.* Consulted April 4th, 2018 at: https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle.
20. Van Stempvoort D, Maathuis H, Jaworski, E, Mayer, B, Rich, K (2005) Oxidation of fugitive methane in ground water linked to bacterial sulfate reduction. *Ground Water* 43(2): 187-199.
21. Kelly WR, Matisoff G, Fisher JB (1985) The effects of a gas well blow out on groundwater chemistry. *Environ Geol and Water Sci* 7(4): 205-213.
22. British Columbia Provincial Greenhouse Gas Emissions Inventory. Available at:

https://www2.gov.bc.ca/gov/content/environment/climate-change/data/provincial-inventory.

23. CAPP (Canadian Association of Petroleum Producers) (2004) *A National Inventory of Greenhouse Gas (GHG), Criteria Air Contamination (CAC) and Hydrogen Sulphide (H_2S) by the Upstream Oil and Gas Industry*. Volumes 1-3, 2004.
24. Lavrov A (2017) Lost circulation in primary well cementing. *Energy Procedia* 114: 5182-5192.
25. Cahill AG, et al. (2017) Mobility and persistence of methane in groundwater in a controlled-release field experiment. *Nat Geosci* 10(4): 289-294.
26. Jackson RE, et al. (2013) Groundwater protection and unconventional gas extraction: The critical need for field-based hydrogeological research. *Ground Water* 51(4): 488-510.
27. Osborn SG, Vengosh A, Warner NR, Jackson, RB (2011) Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proc Natl Acad Sci USA* 108(20): 8172-8176.

Please review all the figures in this paginated PDF and check if the figure size is appropriate to allow reading of the text in the figure.

If readability needs to be improved then resize the figure again in 'Figure sizing' interface of Article Sizing Tool.